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ATTITUDE SENSOR PACKAGE

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This paper describes the design, construction, testing, and successful flight of the Attitude Sensor Package. The payload was assembled on a standard HITCHHIKER experiment mounting plate, and made extensive use of the carrier's power and data handling capabilities. The side mounted HITCHHIKER version was chosen, since this configuration provided the best viewing conditions for the instruments. The combination was successfully flown on board Space Shuttle Columbia (STS-52), in October 1992.

The payload was one of the 14 experiments of the In-Orbit Technology Demonstration Programme (Phase I) of the European Space Agency.

PROJECT ORGANIZATION

The successful flight of the Attitude Sensor Package (ASP) payload was the result of the combined effort of 3 centers. Firstly, the Special Payloads Division (SPD) of the Goddard Space Flight Center (GSFC). Secondly, the In-Orbit Technology Demonstration Programme (TDP) of the European Space Agency (ESA). Thirdly, the companies Officine Galileo of Florence (I) and MACDIT of Lecco (I).

The companies worked under contract to the TDP. Officine Galileo is a European leader in the field of electro-optical instruments for ground and space applications. They have been active in the space market for over 30 years, and have supplied these systems for many European spacecraft. The company performed the system design, and was also responsible for most subsystems. MACDIT worked under subcontract to Officine Galileo, to provide their specific expertise, the mechanical design and manufacture and the thermal design.

ESA's TDP was instituted in 1987 to provide a means of establishing the viability of advanced technologies in the space environment. The first phase of the programme involved 14 different experiments, and the ASP was the most complex of these. With the help of experts of ESA's Technical Directorate, the programme funded and managed the design of the payload, and liaised with the SPD to ensure compatibility with the carrier.

The SPD of GSFC provided the HITCHHIKER carrier, an essential element to accommodate the payload on the Space Shuttle. The group also acted as an interface to other NASA centers to ensure that the payload is safe, and that its operational requirements are met. Extensive facilities are made available to the experimenter to communicate with the payload and the flight control team.

OBJECTIVES OF THE ASP PAYLOAD

The objective of the ASP payload was to test 3 independent spacecraft attitude sensors under realistic conditions in space. To combine the sensors in a single test was particularly attractive, in that they complemented each other and yielded high overall accuracy. The sensors were: the Modular Star Sensor (MOSS), the Low Altitude Conical Earth Sensor (LACES), and the Yaw Earth Sensor (YESS). Each sensor had a specific set of individual test objectives.

The overall accuracy of the MOSS sensor with respect to angular resolution had to be verified, combined with an investigation of sensitivity, the ability to track multiple stars, and the effect of integration time. The sensor was equipped with a baffle to attenuate light from bright celestial bodies, or reflections from orbiter structure. The flight test aimed to demonstrate the effectiveness of the baffle, by exploiting times at which the sensor was exposed to adverse stray light.

The LACES test was expected to determine the overall accuracy of the sensor. Due to its superior accuracy, the MOSS data was to serve as the attitude reference. It also determined the inaccuracies caused by the Earth's deviation from a perfectly round body. Since the sensor operates in the infra-red portion of the spectrum, seasons have an effect on the accuracy. This was to be checked by pointing the sensor to different portions of the horizon.

Also for the YESS, the MOSS served as primary attitude reference to determine the overall sensor accuracy. For the sensor to function, distinctive features on the surface of the Earth are required. This is impossible to simulate, and only a flight test provides adequate data. Featureless areas, such as deserts and oceans, were thought to make positive readings difficult or impossible. A flight test would provide an extensive map of the surface in the spectral range of the sensor, so that global performance can be predicted.

DESCRIPTION OF THE ASP PAYLOAD

The ASP payload consisted of the 3 sensor subsystems, the Interface Master Unit (IMU), the Payload Control Unit (PCU), and a support structure. The entire payload was wrapped in a multilayer insulation.

The purpose of the MOSS sensor is to provide input data to the attitude control system of three-axis-stabilised spacecraft, to provide high accuracy pointing of scientific instruments. It can acquire and track up to five stars simultaneously. The relative instantaneous position of each tracked star is computed with reference to the sensor's $3^\circ \times 4^\circ$ field of view, with an accuracy of better than 2 arc-seconds. Within certain limits, the sensor's ability to detect faint stars can be traded for tracking speed. In the highest sensitivity mode, stars of magnitude 7.8 can still be detected. The ASP payload allowed mode selection to be made by telecommand. The star positions are measured in terms of X-Y pixel coordinates within the field of view, and the magnitude of each star target is also measured. The detector, cooled by a Peltier thermoelectric pump, is a CCD, and is placed in the focal plane of the cathadioptric optical system. The stray light coming from sources outside the MOSS field of view was attenuated with a baffle, which was designed to be effective for Sun and Earth minimum approach angles of 45° and 8° respectively.

The LACES is a two-axis (pitch and roll) infrared Earth sensor suitable for attitude control and Earth pointing of spacecraft and platforms operating at altitudes ranging from 100 to 2000 km. LACES performs a conical scan around its line of sight, analysing the 14 to 16.5 micron infrared band. A threshold system detects temperature changes typical of space/Earth transitions. The measurements yield the time it takes to scan from the space-to-Earth to the Earth-to-space transition, which is related to the pitch and roll angles of the spacecraft. A bolometer is the focal plane of the instrument act as the detector.

The YESS measures the yaw angle of the spacecraft with respect to the velocity vector. This is achieved by viewing the Earth through two mutually perpendicular reticles, consisting of parallel opaque bars, with transparent slits between them. The reticles are at an angle of 45 degrees to the zero-yaw direction. The images are projected onto two infrared pyroelectric detectors. A translating scene causes modulation on either detector output, with a frequency proportional to the yaw angle of translation and to the displacement speed of the image. In the processing electronics, the signal gathered by the two channels is converted into yaw attitude information. The sensor scans a field of view of 6 by 14 degrees, and has an accuracy of better than 0.5° .

Specific interface requirements of the application dictated the design of the electrical sensor interfaces. In this payload, a uniform adaptation to the requirements of the PCU was necessary, which was accomplished by the IMU. It acted as a buffer unit, with specific interfaces toward the sensors, and standard interfaces to the PCU. The IMU also included the power distribution and switching for the sensor boxes.

The PCU acted as the central on-board computer. On the one side it communicated with the IMU, and the other side with the Hitchhiker avionics. The primary data stream was channeled

through the HITCHHIKER Medium Rate Ku-Band channel. A fixed format of 30K-bit/second accommodated variable length data packets, which originated from the sensors. This approach provided the required time independence, since the operation of the sensors was unsynchronized. The HITCHHIKER asynchronous downlink channel held housekeeping and sensor summary information. Sensor on/off and MOSS mode commands could be dispatched through the HITCHHIKER asynchronous uplink. The command execution was either direct, or delayed, according to time information provided by the command.

The ASP structure was designed to mate with a side wall mounted HITCHHIKER configuration (see figure 1). It was roughly box shaped, and made up of six aluminum panels, each machined out of solid aluminum blocks. The panels were attached to the HITCHHIKER experiment mounting plate, so that it formed an integral part of the payload. The purpose of this structure was to elevate the sensors above the Orbiter sill level, to satisfy their complex field of view requirements. Electronic boxes were attached directly to the HITCHHIKER plate and to the lateral panels of the ASP structure. Except for the YESS, which was directly attached to the HITCHHIKER plate, the MOSS and the LACES were accommodated on the top plate of the structure. The total weight of the ASP payload was approximately 130 kg.

For thermal control reasons, the experiment was wrapped with multi-layer insulation blankets. Cooling was accomplished by radiating heat into space. Heaters controlled by thermostats were used on the electronic mounting plate to provide heat input during cold Orbiter attitudes.

FLIGHT RESULTS

The high angular accuracy of the MOSS, in the order of 2 arc-seconds, made it the natural lead instrument of the ASP. The LACES and YESS Earth sensors, by contrast, have a precision of only 4 arc-minutes and 0.5° respectively. Even the attitude measurement system of the Orbiter is less accurate than the MOSS, since it relies on gyro instruments that are periodically recalibrated, using star tracker data. The system accuracy is typically 30 arc-seconds.

Therefore, the MOSS was without comparison. However, while it was not possible to directly validate the absolute measurement accuracy of the MOSS, it was at times possible to make a relative assessment of the sensor's measurement performance. Often, more than one star was tracked by the MOSS simultaneously. In this case, with the help of the orbiter attitude data, the area of the celestial sphere being viewed by the sensor was identified. By correlation of the MOSS data with star catalog data, the relative accuracy and the stability of the sensor was determined.

Besides specific accuracies, the sensors measured attitudes in certain axes. The LACES provided roll and pitch information while the YESS only provided yaw information. The MOSS provided

information of both roll and yaw, thus permitting a cross comparison with, and calibration of the lower accuracy sensors.

MOSS DATA ANALYSIS

During the flight, certain planned sequences of the Space Transportation System (STS) maneuvers and sensor commands were carried out to test specific aspects of the MOSS performance. The main part of the processing of the MOSS sensor output was performed using coordinates of a spherical surface (a part of the celestial sphere referenced to the axes of the sensor), because this has made it easier to account for the movement of stars across the field of view, as well as matching entries in the star catalogue. The conversion from the sensor output took account of the optical distortion as well as the effect of projecting onto the planar surface of the CCD.

The post flight analysis showed that all the MOSS commands from the ground were correctly interpreted and executed. Operating sequences demonstrated the sensor's capabilities in terms of sensitivity, number of stars to be tracked, and integration time. The following sensitivities were observed:

$m_v = 5.89$	at 40 msec integration time
$m_v = 6.94$	at 90 msec integration time
$m_v = 7.91$	at 250 msec integration time

Consistently, the error in magnitude indication with respect to the catalogue data was within its theoretical limit of $0.25 m_v$.

At various attitudes of the STS during the daylight portions of the orbits, the sensor behaviour, at different distances from the earth limb to the centre of the field of view, was analyzed. Full performance in terms of maximum detectable star magnitude was obtained when the angle between the earth's limb and the centre of the field of view was 15° or higher. For more acute angles, the illumination of the detector by stray-light decreases the capability to detect dim stars. Typically, at 10° the detectable limit magnitude was $7.01 m_v$ at 250 mseconds integration time. The reason for this is the limit of the baffle performance. Performance improvement would have been possible by lengthening the baffle. This was not possible due to space limitations.

The ability of the sensor to track fast moving stars was verified. During yaw maneuvers the sensor tracked stars moving through the field of view at a speed of about 300 arcsec/sec, which was well in specification.

Only relative accuracy evaluation could be performed due to the lack of a higher quality absolute attitude reference. At least 2 stars had to be in the field of view. An overall accuracy of 2 arcsec (1σ) was consistently observed.

LACES DATA ANALYSIS

The main objective of the LACES test was the correction of the mathematical mode of the Earth, taking into account the Earth's oblateness and the seasonal effects, and the overall accuracy test. As said before, the MOSS provided the attitude reference for the LACES sensor. The 0.07° overall accuracy approached theoretical predictions. Therefore, the mathematical model is considered valid, and no further refinements are necessary.

In the range of 170° to 360° the LACES sensing is inhibited to avoid false triggers caused by thermal gradients of spacecraft structure in the field of view. The test showed that the sensor regains full accuracy 10° past the inhibited zone. At 7.5° past the inhibition zone, the error increases to 0.1° . At 5° past the error is already 0.5° .

YESS DATA ANALYSIS

During the ASP mission, the YESS sensor showed subnominal behaviour in one of the measurement channels. Excessive noise was the assume cause. Tests carried out after the mission showed that this high level of noise was caused by a degradation of the associated detectors. Although this failure prevented direct yaw measurement, the test results are nevertheless very interesting. For extended periods of time the reading of the good channel provided signals that are proportional to the features on Earth. At the time of writing this article, the full data was not yet surveyed, but it is reasonable to assume that many measurements had been taken over oceans and deserts. The information will be evaluated theoretically, to provide the overall sensor performance.

GROUND INFRASTRUCTURE DESCRIPTION

The ground support equipment (GSE) had the task to support the payloads during the ground processing flow, and certain parts were used also during the flight.

The structure of the GSE allowed easy adaptation to the ground and flight environment. The change could be achieved with a single instruction at the startup of computer 1.

Mechanical Ground Support Equipment

The mechanical ground support equipment (MGSE) of the payload consisted of a transport container that could also be used as a work stand, after the top cover was removed. In the work stand mode, the payload was upright, and allowed easy access to all components.

Electrical Ground Support Equipment

The electrical ground support equipment (EGSE) was composed of three computers and a specially built unit, the 'HITCHHIKER Simulator and Monitoring' Unit (HHSIM).

Computer #1 was dedicated to experiment commanding and the display of housekeeping data. Computer #2 displayed and recorded the Medium Rate Ku-Band data. The initial de-commutation and de-packaging occurred in the HHSIM. Computer #3 displayed the celestial segment within the MOSS sensor's field of view. The primary data originated from a star catalogue, which was read according to the attitude provided by the Orbiter reference.

Payload commands were dispatched from computer #1, using predefined command templates. The commands had packet form, and included a time tag to allow delayed execution. In this way, several orbits were planned and the relevant commands uplinked ahead of time.

PAYLOAD GROUND FLOW

All the three sensors carried their own reflective alignment cubes, to relate their precise mounting orientations to a similar cube located on the experiment structure. Relative alignment was measured before and after the flight, with only small change being detected, demonstrating the high level of stability of the payload assembly.

With the exception of the PCU, most of the environmental tests were conducted on the integrated ASP payload, as opposite to testing at box or sensor level. The PCU was subjected to vibration, thermal-vacuum, and EMC tests. Random vibration test at qualification levels, thermal vacuum, and EMC were then repeated on the ASP payload assembly. The ASP integration with the HITCHHIKER Avionics and a subsequent EMI test was carried out at GSFC. To conduct these tests, GSFC provided the HITCHHIKER ground station and simulators of the Shuttle data link. These units were used in conjunction with the ASP sensors stimulator included in the ASP GSE.

At the Kennedy Space Center (KSC), the ASP payload was subjected to an electrical compatibility tests (CITE), and to an Interface Verification Test (IVT). The objective of these tests was to prove that the payload, connected to the Orbiter power and data system, could receive and correctly execute all the relevant commands.

About two weeks after the landing of STS-52 at KSC, the ASP payload was deintegrated from the Orbiter and transported to ASTROTECH. After carrying out post flight performance testing, the payload was packed and shipped to Italy.

FLIGHT OPERATIONS

The flight operations were conducted from the GSFC Small Payloads Flight Operations Control Center (POCC). The commands could be sent at every orbit of ASP data taking. Each packet set the MOSS in a particular configuration for one or more orbits. Each orbit of data taking corresponded to a test of a particular feature of the star tracker. One orbit, for example, was dedicated to testing the sensor's ability to detect and track dim stars, while another orbit was used to investigate the sensor's performance when set to track the maximum number of stars. Essentially, the YESS and the LACES had optimal operating conditions throughout the flight. A minimum of 16 orbits were needed to completely demonstrate all sensors features. ESA and Galileo personnel operated the ASP payload throughout the Shuttle ten day mission and the number of ASP orbits actually achieved was more than double the minimum required GSE during the 10 day long mission.

Part of the ASP mission was conducted with the Orbiter flying either nose or tail forward, and with the cargo bay facing the Earth. With the Shuttle in this attitude, the MOSS line of sight and the LACES scanning cone axis were directed toward the pole of the orbit. The YESS line of sight was directed toward the centre of the Earth. Then, the MOSS field of view rotates 360 degrees about the center, and essentially the same stars are detected.

The ASP was also operated with the Orbiter in a tail or nose forward attitude, with the cargo bay oriented toward the Earth, but with 5 degrees roll offset away from the Earth. In this attitude, during one orbit, the MOSS field of view described an angulus of 5 degrees radius, and thereby a wider portion of the sky was scanned, with more target stars available. The effect of the 5 degrees roll away from the Earth was also to attenuate the stray light into the star tracker.

The Orbiter also performed a planned flight maneuver with the cargo bay to Earth and the wing pointed along the velocity vector. In this attitude, the MOSS line of sight was tangential to the orbit and the star moved at higher speed through the sensor field of view. This attitude was requested to test the YESS sensor. Additionally, starting from this attitude, the Orbiter also performed a ± 15 degrees rotation about its yaw axis. Shuttle mission embody this concept of flexibility.

Many maneuvers and attitude changes occurred during the flight, most of them according to a previously established flight plan. We were offered the possibility to adjust the plan, to either accommodate difficulties, or to allow further investigation of phenomena observed during the mission. These ad-hoc plans were introduced during the daily operations replanning. This flexibility was experienced as a very valuable feature of the HITCHHIKER system.

CONCLUSIONS

A number of significant results have been achieved in this ASP flight test on board the Shuttle. The preparation of the payload was in itself a very valuable exercise. The optical sensors operated in its intended environment, under illumination and target conditions which cannot realistically be reproduced on ground. The fact that the experiment hardware was retrievable added extra value to the mission because we could perform post flight performance tests.

Although further evaluation of the ASP flight data will continue for some time, the results obtained from the flight are very satisfactory. The data analysis clearly indicates an extremely satisfactory performance by the two primary sensors, the MOSS star sensor and the LACES infra-red sensor. Both units performed in specification, and in particular the MOSS functioned well over a significant range of different observing conditions. In spite of the anomaly suffered by the YESS, enough data has been gathered to characterize the sensors. The future utilization of further development of all the sensors on the ASP will benefit substantially from the experience and results derived from the ASP mission. In fact, the MOSS and the LACES are already foreseen for European space missions.

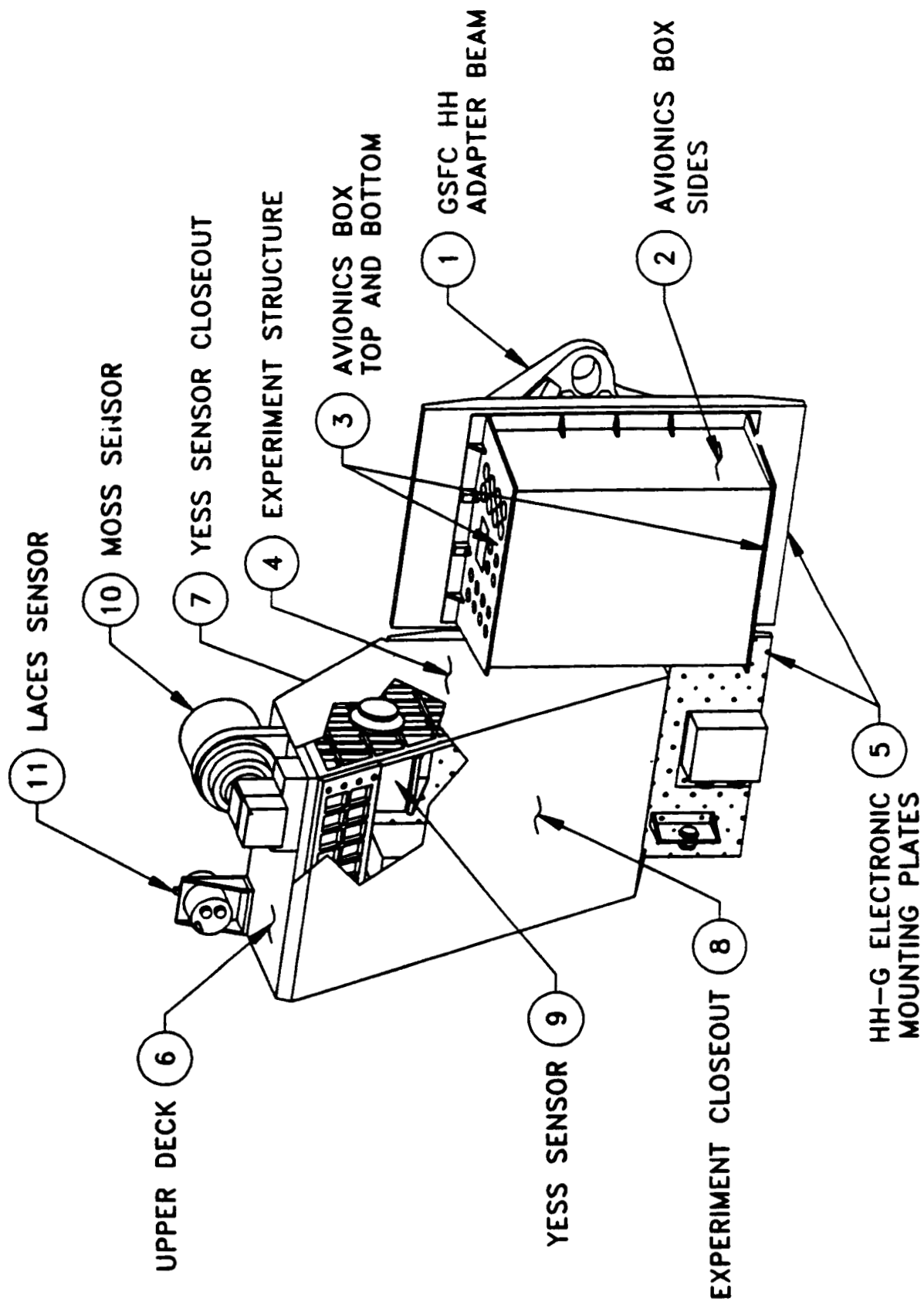


FIGURE 1 - ATTITUDE SENSOR PACKAGE PAYLOAD CONFIGURATION

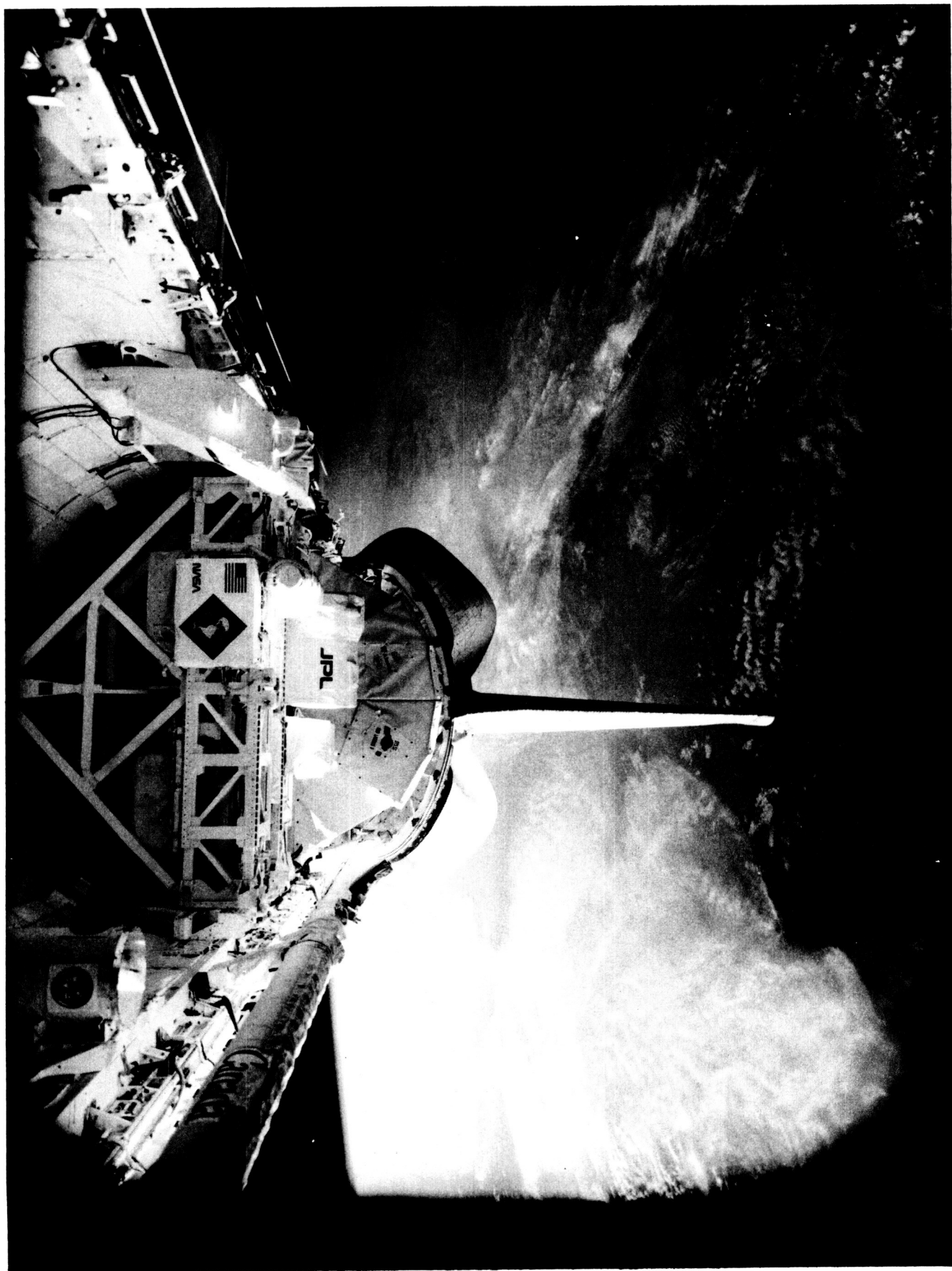


FIGURE 2 - ATTITUDE SENSOR PACKAGE PAYLOAD ON-BOARD STS-52